Key points

- The primary stimulus for exercise-induced bronchoconstriction (EIB) is water loss from the airway surface liquid with subsequent bronchoconstricting mediator release.
- A symptoms-based diagnosis is not sensitive or specific to EIB.
- The free run can be a very effective stimulus to EIB.
- The dry-air laboratory challenge is an effective test for EIB and allows for more control of test intensity and inhaled air conditions than the field-based challenge.
- A positive challenge is defined by a 10% decrease in forced expiratory volume in 1 s from baseline at two time-points within 3–30 min after the cessation of exercise.

Field and laboratory exercise challenges for identifying exercise-induced bronchoconstriction

Educational aims

- › To define necessary conditions for a successful exercise challenge.
- › To provide operational procedures for performing an exercise challenge in the laboratory or the field for the identification of exercise-induced bronchoconstriction.
- › To compare positive and negative attributes of each challenge.
- › To provide spirometric cut-off criteria for positive challenge tests.

Summary

Exercise challenge tests are often used for identification of exercise-induced bronchoconstriction (EIB). Optimal test conditions are: absolute humidity of <10 mg H₂O per L; exercise intensity resulting in a sustained increase in minute ventilation to 14–21 times the forced expiratory volume in 1 s or heart rate (HR) to 80–90% of the estimated maximal HR; and exercise duration of 6–8 min. Variability in fitness level and age necessitate individualisation of the exercise protocol. Field tests are subject to variability in test conditions and may have poorer repeatability than laboratory tests that require expensive equipment. However, either challenge test can be employed for the diagnosis of EIB in conjunction with a critical clinical assessment.

Historical aspects

The association of exercise with asthma was recognised almost 2,000 yrs ago by Aretæus (81–138 AD): "If from running, gymnastic exercises, or any other work, the breathing becomes difficult, it is called Asthma" [1]. Any condition associated with dyspnoea was described as asthma until the publication of "A treatise of the asthma" by Sir John Floyer in 1698 [2]. He suffered from asthma, and described how exercise could precipitate an asthmatic attack and that the severity of the attack is related to

the intensity of the exercise: "All violent Exercise makes the Asthmatic to breathe short ... and if the Exercise be continued it occasions a Fit".

The first objective measurement of the effect of exercise on lung function was made by HERXHEIMER [3] in 1946. In addition to the level of hyperventilation, the magnitude of the response, measured as the decrease in lung function that occurs after exercise, was subsequently shown to be dependent on the nature, intensity and duration of the exercise stimulus. Different exercise forms have been investigated. When performed at similar heart rate (HR), minute ventilation and oxygen consumption,

K.W. Rundell¹
M. Sue-Chu²

¹The Commonwealth Medical College, Scranton, PA, USA, and
²Department of Lung Medicine, St Olav's Hospital, University Hospital of Trondheim, Institute of Circulation and Imaging, Norwegian University of Science and Technology, Trondheim, Norway

Correspondence

M. Sue-Chu
Department of Lung Medicine
St. Olavs Hospital
Postbox 3250 Sluppen
7006 Trondheim
Norway
msuechu@online.no

HERMES syllabus link: D.1.6

the exercise modality that is most potent for the degree and incidence of bronchoconstriction is free running, followed in decreasing order by treadmill running, cycling, swimming and walking (fig. 1) [4]. With regard to duration and intensity, the maximum effect of treadmill running on lung function occurs after 6–8 min running up a slope of 10–15% at a constant speed [5].

Additional factors that influence the effect of exercise are the water content and quality of the inspired air. The water content of the inspired air determines the extent of the respiratory water loss during exercise. It is complexly related to relative humidity and air temperature. At a given temperature, water content is determined by the relative humidity of the air. However, for a given relative humidity, water content is nonlinearly related to temperature. Thus, the water content is always low in cold air, but can vary from low to high in warm air depending on the relative humidity of the air. In susceptible individuals, air with a low water content is more potent than air with a high water content at provoking bronchoconstriction and cooling of the inspired air enhances the airway response [6]. By contrast, warming of the inspired air to or above body temperature does not prevent bronchoconstriction if the relative humidity is low [7].

Two hypotheses were proposed in the late 1970s and early 1980s for the mechanism of EIB [8, 9]. Both are based on the effects of water loss. In the thermal hypothesis, evaporative water loss during exercise leads to airway cooling and vasoconstriction. After exercise, there is rapid rewarming with bronchial vascular engorgement and airway oedema [10]. In the osmotic hypothesis, water loss causes dehydration of the airways, leading to a transient increase in osmolarity [11] with subsequent release of bronchoconstrictive mediators [12]. Critical review of the experimental work leading to both hypotheses suggests that the increase in airway resistance seen in EIB may be

due to both the mechanical effect of the reactive hyperaemia and mediator-induced contraction of the bronchial smooth musculature [13].

EIB

EIB is the transient narrowing of the lower airways that occurs after exercise [14, 15]. Occasionally, transient narrowing can also occur during exercise [16–18]. It occurs in most individuals with recognised asthma, but can also occur in individuals without signs of clinical asthma, such as elite athletes [19].

Cough, wheeze, chest tightness, shortness of breath or excess mucus production are observed symptoms of EIB. However, self-reported symptoms are neither specific nor sensitive for EIB. ~50% of elite athletes who report symptoms in combination with exercise do not have airway narrowing and ~50% who report no symptoms will test positive for EIB [20, 21]. It is therefore important to support the diagnosis of EIB by performing a challenge test.

The exercise challenge test

The exercise challenge test is indicated primarily for the diagnosis of EIB, assessment of EIB severity and the efficacy of prophylactic drug therapy [22]. In some countries it is also used to screen for EIB in elite athletes and in certain occupations, such as firefighters, police and soldiers. It is considered an indirect challenge because it is associated with release of mediators that act on airway smooth muscle to cause contraction. This is unlike the direct challenges of histamine and methacholine, which act directly on the airway smooth muscle receptors to cause bronchoconstriction independent of the presence of inflammatory cells.

Contraindications

Absolute and relative contraindications that are recommended in the European Respiratory Society (ERS) and American Thoracic Society (ATS) guidelines on bronchial provocation testing [22, 23] are summarised in table 1. If baseline forced expiratory volume in 1 s (FEV₁) is <50% predicted or <1.5 L, an exercise challenge should not be performed; a β_2 -agonist reversibility test should be substituted. A challenge test should only be done if the expected benefit justifies

Figure 1

When performed at the same metabolic rate, running is the most potent exercise modality for exercise-induced bronchoconstriction. Diamonds: swim; circles: ergometer; triangles: treadmill; squares: free run. Arrows indicate administration of a bronchodilator. Modified from [4], with permission from the publisher.

the potential risk and complications associated with the procedure. Preferably, exercise challenge should be performed in subjects with lung function 75–100% predicted.

Subject preparation

In addition to antiasthmatic medication and medication with antihistamine effects, the subject should abstain from all food and drinks that contain caffeine, and strenuous exercise. Abstinence times before the exercise test are given in table 2.

Measurement of lung function

Lung function tests should follow ATS and ERS standards for forced vital capacity and FEV₁ manoeuvres [24]. Spirometry should be performed at baseline prior to the exercise challenge. The 10% decrease and 50% alert value of FEV₁ should be calculated from the pre-exercise baseline FEV₁. After challenge, spirometry is performed at defined times, such as 3, 5, 10, 15, 20 and 30 min. It is not recommended at earlier time points after challenge, as the effort could

be influenced by respiratory muscle fatigue [25]. Spirometry should continue to 30 min unless the patient has a decrease in FEV₁ >50%, at which point a shortacting β_2 -agonist should be administered to reverse the response. At each time-point, two repeatable FEV₁ values should be measured and the greater of the two values recorded. The patient should not be released until FEV₁ returns to 95% of the baseline value.

Post-exercise FEV₁ values are compared with pre-exercise baseline FEV₁ values and calculated as a % change from baseline using the equation:

$$\frac{\text{Pre-exercise FEV}_1 - \text{postexercise FEV}_1}{\text{pre-exercise FEV}_1} \times 100$$

A $\geq 10\%$ decline in FEV₁ at any time-point within 30 min of ceasing exercise is considered diagnostic of EIB [22, 23]. The optimal cut-off point in children and adolescents is considered to be a $\geq 13\%$ decline in FEV₁ [26, 27]. The decline in FEV₁ is usually sustained over two time-points. An unsustained decline may be due to respiratory muscle fatigue.

Table 1 Comparison of absolute and relative contraindications to exercise challenge tests from the guidelines of the European Respiratory Society (ERS) and the American Thoracic Society (ATS)

	Factor	ATS	ERS
Absolute	Severe airflow limitation (FEV ₁ <50% pred or <1 L)	x	
	Severe airflow limitation (FEV ₁ <1.2 L in adults)		x
	Heart attack in last 3 months	x	x
	Stroke in last 3 months	x	x
	Uncontrolled hypertension (systolic BP >200 mmHg or diastolic BP >100 mmHg)	x	
	Aortic aneurysm	x	
	Arterial aneurysm		x
	Inability to understand the procedures and the implications of a challenge test		x
	Unstable cardiac ischaemia or malignant arrhythmias	x	
Relative	Moderate airflow limitation (FEV ₁ <60% pred or <1.5 L)	x	
	Moderate airflow limitation (FEV ₁ < predicted FEV ₁ – 1.5 L in males, FEV ₁ < predicted FEV ₁ – 1.2 L in females)		x
	Inability to perform acceptable-quality spirometry	x	
	Pregnancy	x	x
	Nursing mothers	x	
	Current use of cholinesterase inhibitor medication (for myasthenia gravis)	x	
	Recent upper respiratory tract infection (<2 weeks)		x
	During exacerbations of asthma		x
	Epilepsy requiring drug treatment		x

% pred: % predicted; BP: blood pressure. #: for safety reasons, exercise challenge tests should preferably be performed in subjects with lung function 75–100% pred.

Table 2 Minimum abstention times for medication, exercise and nutrients prior to exercise challenge test

Minimum abstention time	Factor
Day of test	Coffee, tea, cola drinks and chocolate Smoking
4 h	Strenuous exercise
6–8 h	Short-acting, inhaled β_2 -agonists <i>e.g.</i> salbutamol and terbutaline Short-acting anticholinergics <i>e.g.</i> ipratropium Chromones <i>e.g.</i> cromolyn sodium and nedocromil
12–24 h	Long-acting, inhaled β_2 -agonists <i>e.g.</i> salmeterol and formoterol Inhaled glucocorticosteroid
24 h	Theophylline
48 h	Ultralong-acting, inhaled β_2 -agonists <i>e.g.</i> indacaterol
72 h	Long-acting anticholinergics <i>e.g.</i> tiotropium Leukotriene receptor antagonists Antihistamines and other medications with antihistamine effects <i>e.g.</i> tricyclic antidepressants

Exercise testing protocols

Both the ERS and ATS have published guidelines for exercise test protocols [22, 23]. Pre-exercise warm-up is not allowed, as this has been shown to be protective to EIB in some individuals. A nose clip is always worn during the test to dictate mouth breathing and prevent the inspired air from being conditioned by the nasal mucosa.

The target workload should be sufficient to increase the minute ventilation to 14–21 times the predicted FEV₁, which is 40–60% of the maximum voluntary ventilation (MVV), defined as 35×FEV₁. It should be achieved within 2–4 min of the start of the challenge and then be sustained for a further 4 min, with a total time of 6 min for children, 7 min for adolescents and 8 min for adults. The work intensity that is necessary to achieve the target work load is dependent on the degree of physical fitness and body weight of the subject. Degree of physical fitness is of equal importance for all exercise modalities, as is the age of the patient. Because of the wide age range of patients, no single standardised protocol pace can be defined. The protocol should be individualised according to fitness level and age. Body weight is of lesser importance for the work intensity on a cycle ergometer.

It is essential that a high level of minute ventilation is rapidly achieved and maintained for the duration of the test in order for rapid recruitment of the lower airways to the 10th generation to occur, allowing conditioning of the inspired air. According to the osmotic hypothesis, the rate of water loss is more important than the absolute water loss for an increase in osmolarity of the

periciliary fluid and subsequent release of mediators leading to EIB.

The inhaled air should be dry, with a water content <10 mg H₂O per L of air. Relative humidity (RH) and ambient temperature of the inspired air should always be measured. The relationship between these two factors to give an absolute water content of 10 mg H₂O per L is shown in figure 2 [26]. For laboratory tests, medical grade air (<5 mg H₂O per L) is preferred and is administered using a nonlatex reservoir bag with a two-way, nonbreathing mouth valve.

Exercise tests can be performed in the laboratory or in the field. Ergometers, such as the motor-driven treadmill or bicycle, are needed for laboratory tests, while field tests are either free running or a sport-specific exercise. For the elite athlete, a sport-specific exercise test is often used and should be performed under conditions that cause symptoms in the subject.

Monitoring

It is recommended that minute ventilation is monitored during the exercise challenge to ensure that the exercise targets are achieved. Minute ventilation is typically measured online using a metabolic cart during the laboratory exercise challenge. This allows the technician to increase, maintain or decrease the speed and/or incline of the treadmill to reach the target ventilation of 50–60% MVV. If minute ventilation cannot be monitored, HR in beats per min can be used as a surrogate, with a target HR of 80–90% estimated HR_{max} (220 – age in yrs) for the last 4 min of the challenge [22]. An exercising HR of 80–90% will allow all but the very fit elite athlete to achieve and exceed 60% MVV.

HR can be monitored simply by using a wireless HR monitor watch and chest band during laboratory and field exercise tests. Alternatively, ECG equipment with a three-lead or 12-lead placement can be used for laboratory exercise tests.

Safety aspects

During all exercise challenges, personnel qualified to administer emergency procedures should be present. Emergency equipment, such as a cardiodefibrillator, materials for intubation and emergency rescue medication, should be readily available.

Sensitivity and specificity

For both laboratory and field tests, the minute ventilation achieved and sustained during the exercise, the duration of the exercise and the

Treadmill exercise

The work intensity on the treadmill is determined by the speed and slope of the treadmill and the weight of the subject [28, 29]. General recommendations for starting treadmill speed are 3 km · h⁻¹ for children and 5 km · h⁻¹ for adults at an incline of 2.5% [30]. In some protocols, the desired work intensity is achieved by increasing the slope while running at a constant speed; in other protocols, both slope and speed are increased in order to reach the work intensity within the first 2 min of the challenge. Prior to 2 min, adjustments should be made to achieve the target of 80–90% of predicted maximum HR (HR_{max}) and a minute ventilation of 50–60% predicted MVV. Further adjustments can be made up to minute 4. The target HR/minute ventilation should be maintained for the remaining 4 min of the challenge.

Cycle ergometer

The target workload in W in the healthy untrained subject is calculated using as $(53.76 \times \text{predicted FEV1}) - 11.07$ [31]. This is achieved within 4 min by beginning at 60% of the target workload and increasing at 1-min intervals to 70, 90 and 100%. The subject should be encouraged to sustain this target workload for an additional 4 min. At this workload the minute ventilation should reach 50–60% of predicted MVV.

Free-running

Subjects are encouraged to run as fast as possible on an indoor or outdoor track. In children, the running time is standardised to 6 min and a HR of 85–90% of predicted HR_{max} is achieved within 2 min, which is then sustained for 4 min [26].

In adolescent athletes, a minimum running time of 6 min or a standard distance of 1 mile of competitive running in groups of four to six subjects has been used [32].

Sport-specific exercise tests

Sport-specific tests have been used in athletes in winter sports, such as cross-country and biathlon skiers, speed skaters, ice hockey players, and swimmers [33–38]. All protocols were at competition intensity, but varied regarding presence or absence of warm-ups. The duration of the exercise test is dependent on the sport of the athlete and can vary from 80 s in speed skaters to >1 h in cross-country skiers [39].

Alternatively, the duration can be constant, being usually 6–15 min [34, 35, 38–40], or it can be a race over a fixed distance [37, 38].

water content of the inspired air are factors that determine the sensitivity and specificity of the challenge. The currently recommended exercise challenge for EIB is 8 min exercise (either cycling or running) that evokes an intensity >90% HR_{max} by 2–4 min into the challenge and is maintained for the remaining 4–6 min. The exercise challenge should not be done at ambient conditions with an absolute humidity >10 mg H₂O per L (e.g. 21 °C, 60% RH), as this increases the risk of a false negative test [41]. In field-based tests, ambient temperature, wind velocity, and air pollution with allergens, chemicals, ozone and particulate matter are additional factors that may affect the airway response [42].

Irrespective of the type of exercise challenge, it is essential that a high level of minute ventilation is rapidly achieved and maintained for the test duration in order for rapid recruitment of the lower airways to the 10th generation to occur for conditioning of the inspired air.

Free running and sport-specific exercise challenges [18, 33, 34, 36, 43] are valid for the evaluation of EIB if performed under appropriate conditions. They are more sensitive than laboratory challenges at an ambient temperature of 21 °C, 60% RH and an exercise intensity of 95% predict HR_{max} [39]. In one study, 18 out of 23 athletes who tested positive for EIB using field-based challenge tested normal in an ambient-conditions laboratory challenge (fig. 3).

Effect of HR_{max}

The sensitivity of the exercise challenge is increased if the HR response to the workload is increased from 85% to 95% HR_{max}. CARLSEN *et*

Figure 2

The shaded area represents the conditions of ambient temperature and relative humidity resulting in an absolute water content <10 mg H₂O per L of air, which is suitable for exercise testing. Modified from [26], with permission from the publisher.

Figure 3

Mean $\pm$ SE post-challenge decreases in forced expiratory volume in 1 s comparing a cold-air, field-based exercise challenge to a room temperature (21°C, 50% relative humidity) laboratory exercise challenge (n=18). 18 out of 23 subjects were exercise-induced bronchoconstriction (EIB)-positive after a field challenge and -negative after the laboratory challenge. Only five out of 23 EIB "field"-positive subjects tested positive in both challenges. Data from [39].

al. [44] examined the effect of exercise intensity on EIB by comparing the results of two treadmill challenge tests at 85% and 95% of calculated HR_{max} in 20 asthmatic children. The peak decrease in FEV₁ was significantly greater at 95% than at 85% HR_{max} (25.11% versus 8.84% decrease); nine out of 20 subjects had decreases >10% at 85% HR_{max}, while all 20 had decreases >10% at 95% HR_{max}. This study supports the necessity of standardising the exercise protocol using high exercise intensity and consequent high minute ventilation.

Effect of cold air

The temperature of the inspired air does not affect the sensitivity of the challenge. However, it may affect the severity of the EIB. When exercise challenge was performed at the same RH (40%) but at temperatures of 20.2°C and -18°C, the severity of the EIB was significantly greater after exercise at -18°C than at 20.2°C, suggesting an additive effect of cold air [45]. Thus, it may be prudent to assess individuals who have symptoms only under cold conditions with an exercise challenge with cold air inhalation if the challenge test with warm air with an absolute humidity <10 mg H₂O per L is negative. In contrast, no additive effect was observed by EVANS *et al.* [46], who reported that the severity of EIB was related to water content and not the temperature of inhaled air during exercise.

Repeatability

In a study examining the repeatability of % decrease in FEV₁ in 373 subjects with mild symptoms suggestive of asthma but without a

definitive diagnosis, PEARLMAN *et al.* [47] identified agreement between two laboratory exercise challenges of 76.1%. 56.8% of the subjects were negative on both challenges, 19.3% were positive on both challenges and 23.9% had a positive test on only one challenge [47].

In another study of subjects with symptoms suggestive of asthma, a well controlled laboratory exercise challenge demonstrated reasonable repeatability, but intersubject variability suggests that two tests may be needed to make a diagnosis of EIB [48].

Using a 15% decrease in FEV₁ as the cut-off criterion for a positive test, HABY *et al.* [49] showed good validity and short-term reliability of free running in evaluating EIB in large groups of children 8–11 yrs of age. However, the uncontrolled nature of the stimulus and changing ambient conditions may impose variability that limits the free running test as a means of monitoring therapy.

Conclusion

The exercise challenge test for identification of EIB can be problematic. If the inhaled air is not sufficiently dry, or if the exercise intensity is not sufficient to achieve a minute ventilation of 14–21×FEV₁ or 80–90% estimated HR_{max}, then false negative tests are likely. If these conditions are met then the test can be highly sensitive. Because of variability in patient fitness level and age of patients, it is not practical to have a defined laboratory challenge protocol in terms of treadmill speed and incline or cycle ergometer intensity. Even with consistent within-patient protocols, the agreement between two laboratory treadmill challenges is 76%. The ease in administering the field-based challenge and the lack of required expensive equipment make this challenge attractive. This challenge has been called the “gold standard”. However, because of the variability in exercise intensity and ambient conditions from one test day to another, this test is not ideal for monitoring therapy. In conclusion, the exercise challenge can be a useful tool for the identification of EIB, but as with all challenge tests, it is only one piece of the diagnostic puzzle, which includes close evaluation of symptoms, atopic status, family history and clinical examination, together with response to bronchodilators and oral corticosteroids.

References

1. Adams F. The extant works of Aretæus, the Cappodocian. London, The Sydenham Society, 1856.
2. Sakula A. Sir John Floyer's A Treatise of the Asthma (1698). *Thorax* 1984; 39: 248–254.
3. Herxheimer H. Hyperventilation asthma. *Lancet* 1946; 247: 83–87.
4. Anderson SD, Silverman M, König P, et al. Exercise-induced asthma. *Brit J Dis Chest* 1975; 69: 1–39.
5. Silverman M, Anderson SD. The standardization of exercise tests in asthmatic children. *Arch Dis Childh* 1972; 47: 882–889.
6. Strauss RH, McFadden Jr ER, Ingram Jr RH, et al. Influence of heat and humidity on the airway obstruction induced by exercise in asthma. *J Clin Invest* 1978; 61: 433–440.
7. Anderson SD, Schoeffel RE, Black JL, et al. Airway cooling as the stimulus to exercise-induced asthma – a re-evaluation. *Eur J Respir Dis* 1985; 67: 20–30.
8. McFadden ER, Ingram RH. Exercise-induced asthma: observations on the initiating stimulus. *N Engl J Med* 1979; 301: 763–769.
9. Anderson SD. Is there a unifying hypothesis for exercise-induced asthma? *J Allergy Clin Immunol* 1984; 73: 660–665.
10. McFadden ER, Lenner KA, Strohl KP. Postexertional airway rewarming and thermally induced asthma. *J Clin Invest* 1986; 78: 18–25.
11. Smith CM, Anderson SD. Hyperosmolarity as the stimulus to asthma induced by hyperventilation? *J Allergy Clin Immunol* 1986; 77: 729–36.
12. Anderson SD, Daviskas E. The airway microvasculature and exercise induced asthma. *Thorax* 1992; 47: 748–752.
13. Anderson SD, Daviskas E. The mechanism of exercise-induced asthma is... *J Allergy Clin Immunol* 2000; 106: 453–459.
14. McFadden Jr ER, Gilbert IA. Exercise-induced asthma. *N Engl J Med* 1994; 330: 1362–1367.
15. Anderson SD, Holzer K. Exercise-induced asthma: is it the right diagnosis in elite athletes? *J Allergy Clin Immunol* 2000; 106: 419–428.
16. Beck KC, Offord KP, Scanlon PD. Bronchoconstriction occurring during exercise in asthmatic subjects. *Am J Respir Crit Care Med* 1994; 149: 352–357.
17. Suman OE, Beck KC, Babcock MA, et al. Airway obstruction during exercise and isocapnic hyperventilation in asthmatic subjects. *J Appl Physiol* 1999; 87: 1107–1113.
18. Rundell KW, Spiering BA, Judelson DA, et al. Bronchoconstriction during cross-country skiing: is there really a refractory period? *Med Sci Sports Exerc* 2003; 3: 18–26.
19. Rundell KW, Slee JB. Exercise and other indirect challenges to demonstrate asthma or exercise-induced bronchoconstriction in athletes. *J Allergy Clin Immunol* 2008; 122: 238–246.
20. Rundell KW, Im J, Mayers LB, et al. Self-reported symptoms and exercise-induced asthma in the elite athlete. *Med Sci Sports Exerc* 2001; 33: 208–213.
21. Parsons JP, Kaeding C, Phillips G, et al. Prevalence of exercise-induced bronchospasm in a cohort of varsity college athletes. *Med Sci Sports Exerc* 2007; 39: 1487–1492.
22. Crapo RO, Casaburi R, Coates AL, et al. Guidelines for methacholine and exercise challenge testing – 1999. *Am J Respir Crit Care Med* 2000; 161: 309–329.
23. Sterk PJ, Fabbri LM, Quanjer PH, et al. Airway responsiveness. Standardised challenge testing with pharmacological, physical and sensitizing stimuli in adults. *Eur Respir J* 1993; 6: Suppl. 16, 53–83.
24. Miller MR, Hankinson J, Brusasco V, et al. Standardisation of spirometry. *Eur Respir J* 2005; 26: 319–338.
25. Fitch KD, Sue-Chu M, Anderson SD, et al. Asthma and the elite athlete: summary of the International Olympic Committee's consensus conference, Lausanne, Switzerland, January 22–24, 2008. *J Allergy Clin Immunol* 2008; 122: 254–260.
26. Haby MM, Anderson SD, Peat JK, et al. An exercise challenge protocol for epidemiological studies of asthma in children: comparison with histamine challenge. *Eur Respir J* 1994; 7: 43–49.
27. Godfrey S, Springer C, Bar-Yishay E, et al. Cut-off points defining normal and asthmatic bronchial reactivity to exercise and inhalation challenges in children and young adults. *Eur Respir J* 1999; 14: 659–668.
28. Givoni B, Goldman RF. Predicting metabolic energy cost. *J Appl Physiol* 1971; 30: 429–433.
29. Silverman M, Anderson SD. Metabolic cost of treadmill exercise in children. *J Appl Physiol* 1972; 33: 696–698.
30. Franklin BA, Balady GJ. ACSM's Guidelines for Exercise Testing and Prescription, 6th Edn. Michigan, Lippincott Williams & Wilkins, 2006.
31. Anderson SD, Lambert S, Brannan JD, et al. Laboratory protocol for exercise asthma to evaluate salbutamol given by two devices. *Med Sci Sports Exerc* 2001; 6: 893–900.
32. Kukafka DS, Ciccolella D, D'Alonzo Jr GE, et al. Exercise-induced bronchospasm in high school athletes via a free running test: incidence and epidemiology. *Chest* 1998; 114: 1613–1622.
33. Wilber RL, Rundell KW, Szmedra L, et al. Incidence of exercise-induced bronchospasm in Olympic winter sport athletes. *Med Sci Sports Exerc* 2000; 32: 732–737.
34. Ogston J, Butcher JD. A sport-specific protocol for diagnosing exercise-induced asthma in cross-country skiers. *Clin J Sport Med* 2002; 12: 291–295.
35. Sue-Chu M, Brannan JD, Anderson SD, et al. Airway hyperresponsiveness to methacholine, adenosine 5-monophosphate, mannitol, eucapnic voluntary hyperpnea and field exercise challenge in elite cross-country skiers. *Br J Sports Med* 2010; [Epub ahead of print DOI: 10.1136/bjism.2009.071043].
36. Mannix ET, Farber MO, Palange P, et al. Exercise-induced asthma in figure skaters. *Chest* 1996; 109: 312–315.
37. Stensrud T, Mykland KV, Gabrielsen K, et al. Bronchial hyperresponsiveness in skiers: field test versus methacholine provocation? *Med Sci Sports Exerc* 2007; 39: 1681–1686.
38. Pedersen L, Winther S, Backer V, et al. Airway responses to eucapnic hyperpnea, exercise, and methacholine in elite swimmers. *Med Sci Sports Exerc* 2008; 40: 1567–1572.
39. Rundell KW, Wilber RL, Szmedra L, et al. Exercise-induced asthma screening of elite athletes: field versus laboratory exercise challenge. *Med Sci Sports Exerc* 2000; 32: 309–316.
40. Clearie KL, Williamson PA, Vaidyanathan S, et al. Disconnect between standardized field-based testing and mannitol challenge in Scottish elite swimmers. *Clin Exp Allergy* 2010; 40: 731–737.
41. Rundell KW, Anderson SD, Spiering BA, et al. Field exercise versus laboratory eucapnic voluntary hyperventilation to identify airway hyperresponsiveness in elite cold weather athletes. *Chest* 2004; 125: 909–915.
42. Pierson WE, Blerman W. Free running test for exercise-induced bronchospasm. *Pediatrics* 1975; 56: 890–892.

Educational questions

Which statement is correct?

1. With regards to an appropriate exercise challenge:

- a) Inhaled air conditions do not matter but exercise intensity does
- b) Exercise intensity matters; inhaled air conditions do not
- c) Inhaled air should be dry and exercise intensity should be $\geq 80\%$ of estimated maximal heart rate

2. With regards to a positive challenge according to ATS and ERS criteria:

- a) The post-exercise decrease in FEV₁ should be $\geq 6\%$
- b) The post-exercise decrease in FEV₁ should be $\geq 10\%$
- c) The post-exercise decrease in FEV₁ should be $\geq 20\%$

3. With regards to performing an exercise challenge test for EIB, the baseline FEV₁ should be:

- a) $>50\%$ predicted
- b) $>70\%$ predicted
- c) $>85\%$ predicted

4. With regards to a field-based exercise challenge test for EIB:

- a) This challenge is appropriate for monitoring treatment
- b) Exercise conditions can cause variability in test results
- c) Only a free run is appropriate

43. Provost-Craig MA, Arbour KS, Sestili DC, *et al.* The incidence of exercise-induced bronchospasm in competitive figure skaters. *J Asthma* 1996; 33: 67–71.
44. Carlsen KH, Engh G, Mørk M. Exercise-induced bronchoconstriction depends on exercise load. *Respir Med* 2000; 94: 750–755.
45. Stensrud T, Berntsen S, Carlsen K-H. Exercise capacity and exercise-induced bronchoconstriction (EIB) in a cold environment. *Respir Med* 2007; 101: 1529–1536.
46. Evans TM, Rundell KW, Beck KC, *et al.* Cold air inhalation does not affect the severity of EIB after exercise or eucapnic voluntary hyperventilation. *Med Sci Sports Exerc* 2005; 37: 544–549.
47. Pearlman D, Anderson SD, Charlton B, *et al.* Concordance of results from repeat exercise challenges. *J Allergy Clin Immunol* 2008; 121: S209.
48. Dahlén B, O’Byrne PM, Watson RM, *et al.* The reproducibility and sample size requirements of exercise-induced bronchoconstriction measurements. *Eur Respir J* 2001; 17: 581–588.
49. Haby MM, Peat JK, Mellis CM, *et al.* An exercise challenge for epidemiological studies of childhood asthma: validity and repeatability. *Eur Respir J* 1995; 8: 729–736.

Further reading

Rundell KW, Slee JB. Exercise and other indirect challenges to demonstrate asthma or exercise-induced bronchoconstriction in athletes. *J Allergy Clin Immunol* 2008; 122: 238–246.